9-15-2019

Biochar beyond carbon sequestration: Life-cycle emission reductions, nutrient recycling and food security

Johannes Lehmann

Biochar Beyond Carbon Sequestration: Life-Cycle Emission Reductions, Nutrient Recycling and Food Security

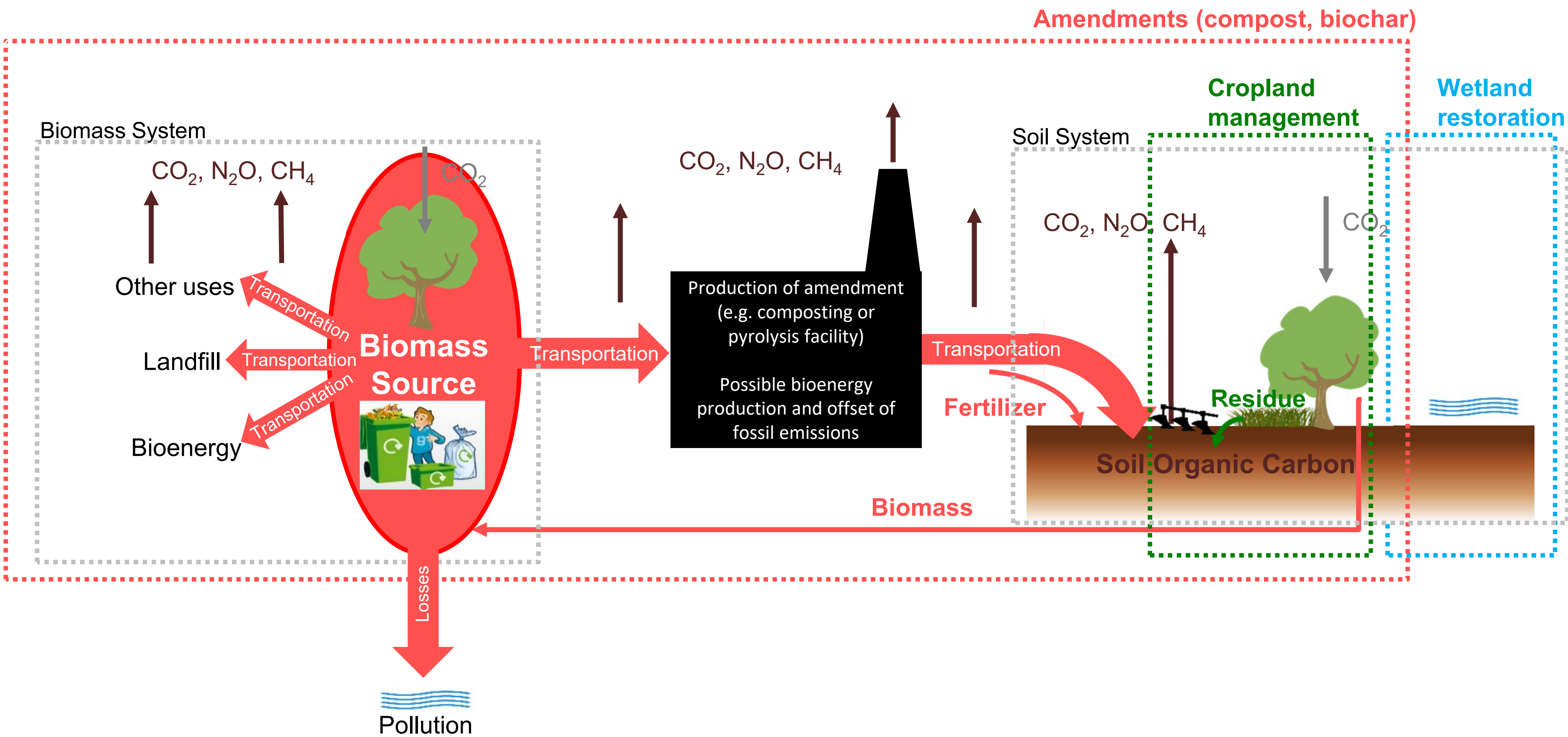
Johannes Lehmann

Cornell University, USA

Abstract

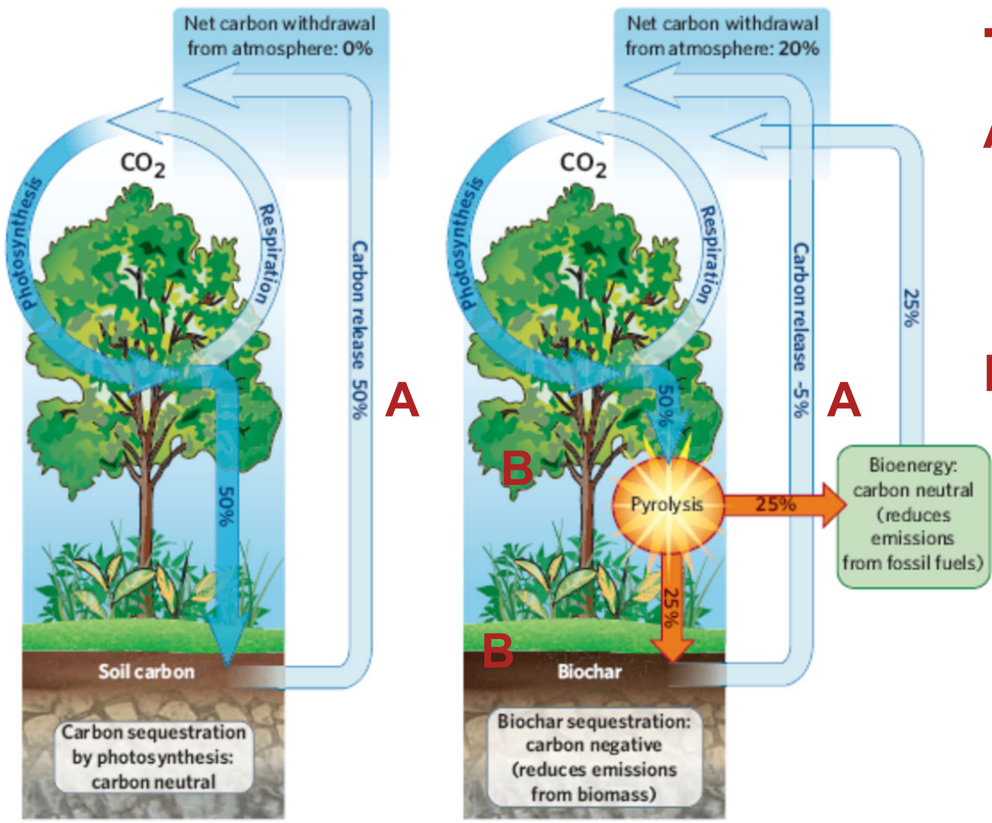
Biochar is by now recognized as a carbon dioxide removal (CDR) approach in climate change mitigation scenarios. Less clear is its framing as an approach for soil carbon sequestration. We posit that biochar carbon sequestration has all the traits of CDR through soil carbon management, with respect to greenhouse gas abatement and co-benefits for food production. Similar to compost, biochar is typically produced off-soil, and a life-cycle emission balance is required to quantify impact. The fact that biochar production by pyrolysis can generate energy products from the concurrent evolution of gases may position biochar as a hybrid engineering-biological approach. However, the CDR is still delivered by photosynthesis and biochar improves soil fertility. Here we argue that many forms of SOC sequestration have implicit tradeoffs with food security when they are scaled globally, whereas this is not the case with soil amendments such as biochar or compost from non-competitive biomass resources. Other advantages of biochar for soil carbon sequestration arise from its persistence in soil, allowing one-time or periodic applications, and the capacity to estimate sequestration from the chemical composition of the biochar, both facilitating implementation and avoiding the need for soil sampling for monitoring and verification.

Soil Carbon Sequestration System Types



Cornell University

Biochar Climate Mitigation



Two Entry Points:

A: Soil CDR <u>and</u> emission reduction through pyrolysis: reduce $CO_2/N_2O/CH_4$ return of the charred OM

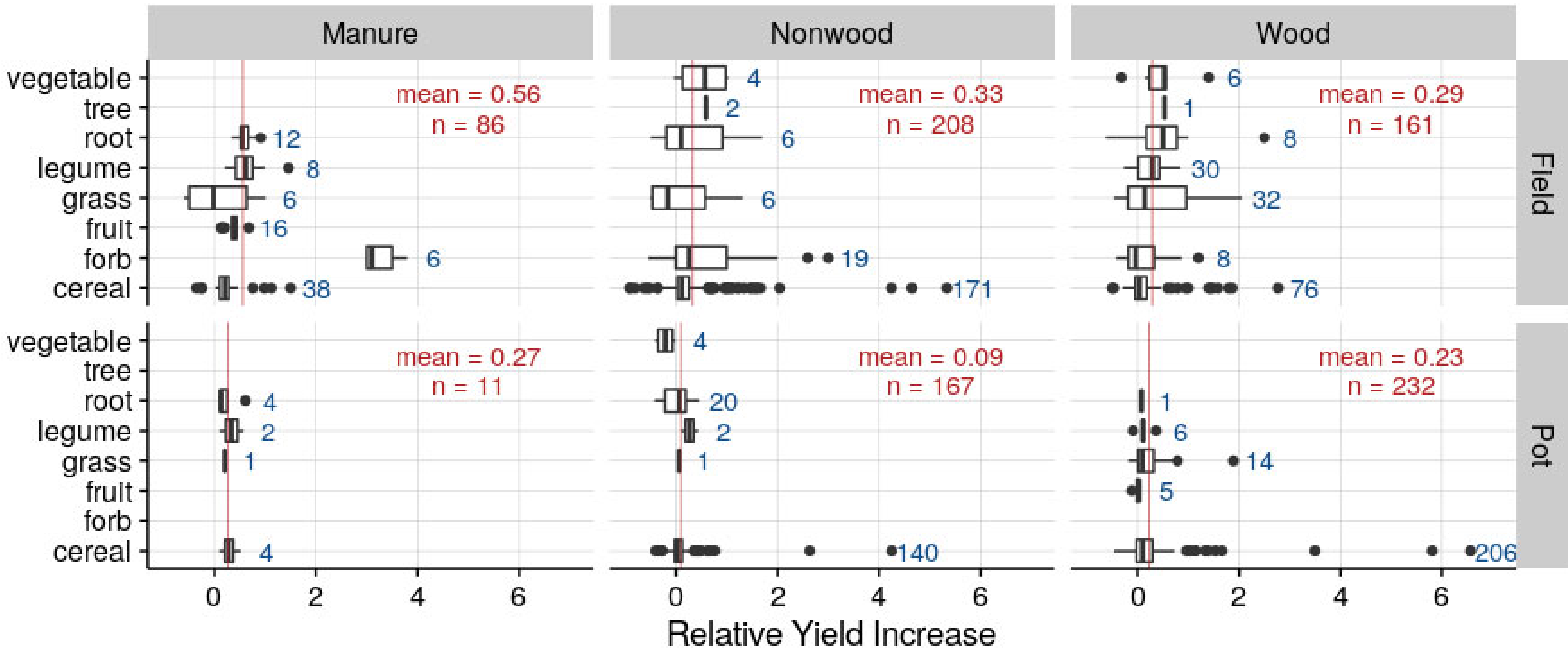
B: Soil CDR <u>and</u> emission reduction through soil application:
B1: reduce soil GHG emissions ($CO_2/N_2O/CH_4$)
B2: increase CO_2 capture by plants through photosynthesis

Lehmann, 2007

Crop Yield Responses

Global crop yield responses
+11-28% (meta-analyses‡)

Soil productivity value

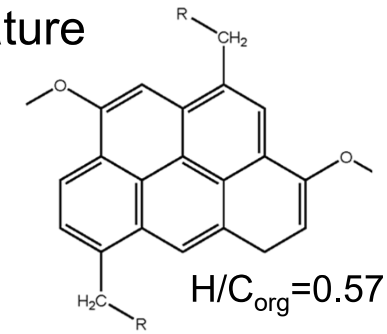


Cornell University

Woolf et al., 2018, Adv. Soil Sci.
‡Jeffery et al. 2011 AEE, 2015; 2017 Env Res Lett; Liu et al., 2011; Ye et al., Soil Use Manage in press

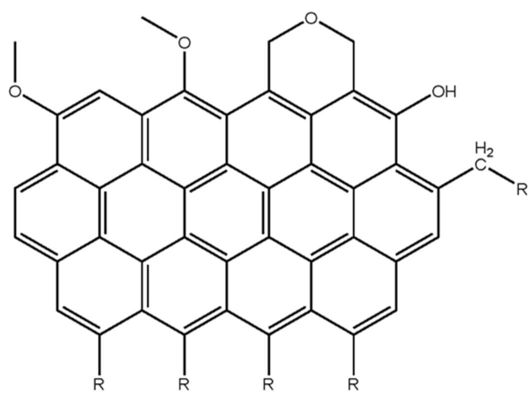
Molecular Properties - Persistence

Low temperature



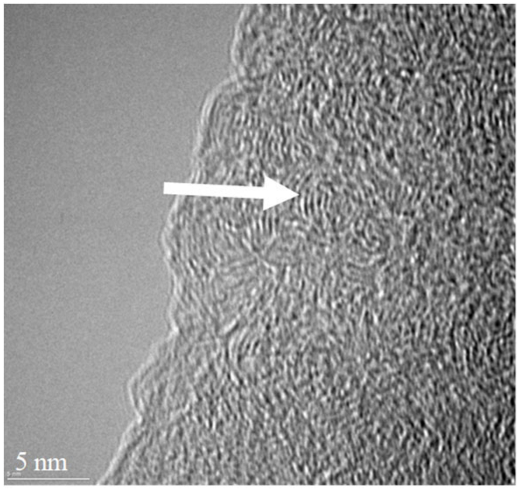
H/C_{org}=0.57

High temperature



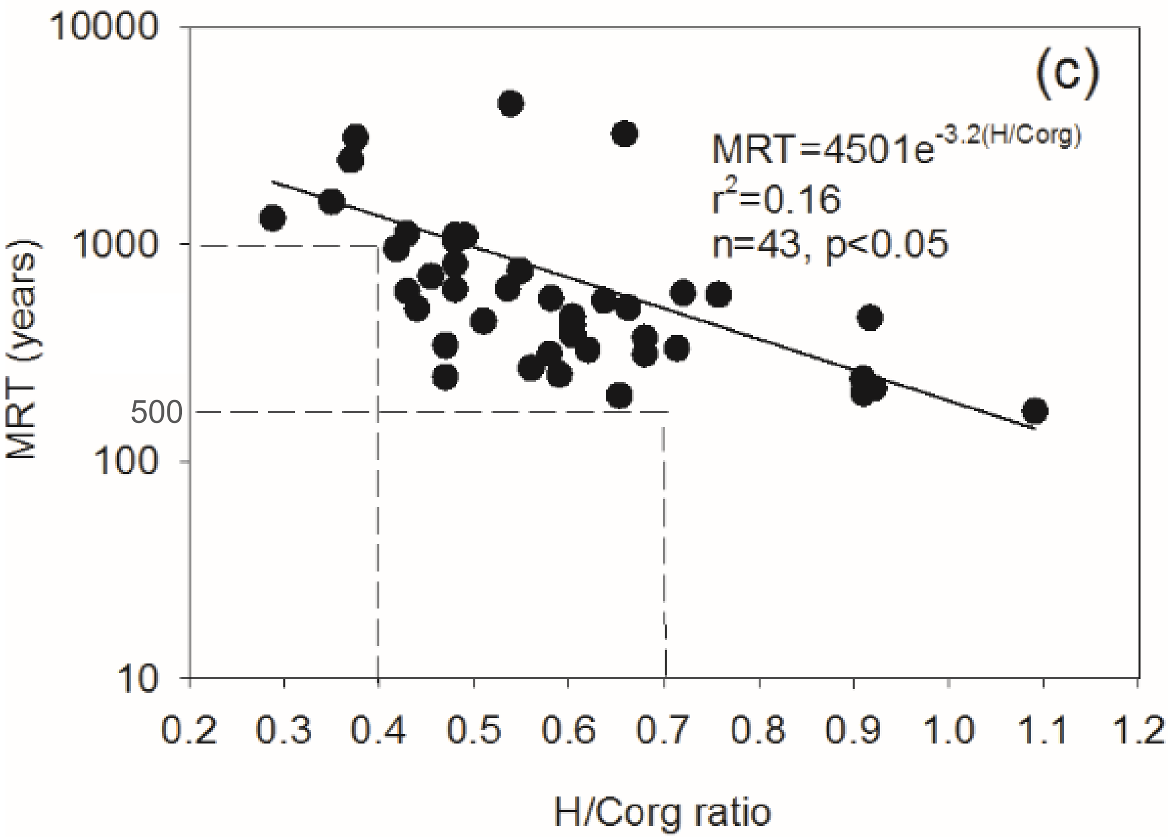
H/C_{org}=0.42

"Small" cluster sizes:
18-40 C from oak wood and corn residues at 350° C and 600° C
25 to 52 C from chestnut wood between 500° C and 700° C
20 or more C in Midwestern Mollisol and Amazonian Dark Earth



Nguyen et al, 2010, EST 44, 3324–3331
McBeath et al, 2011, OG 42, 1194-1202
Mao et al, 2012, EST 46, 9571-9576

Persistence in Soil

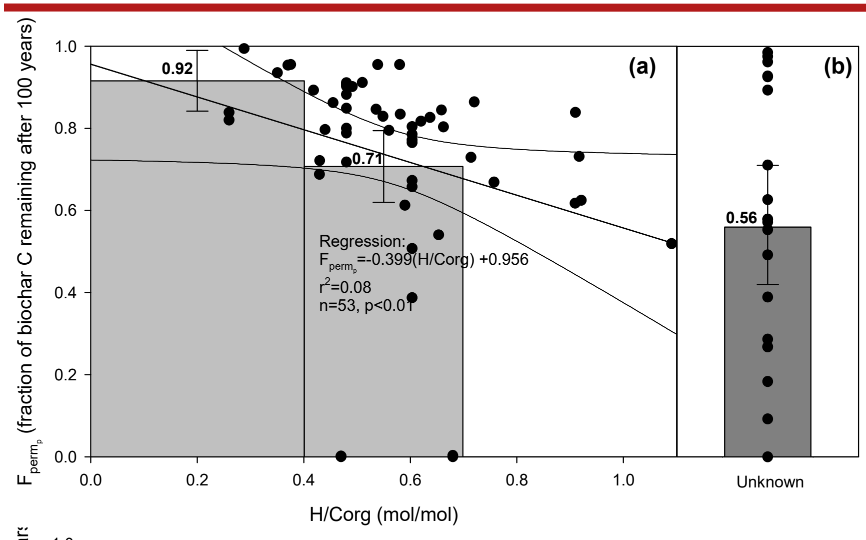


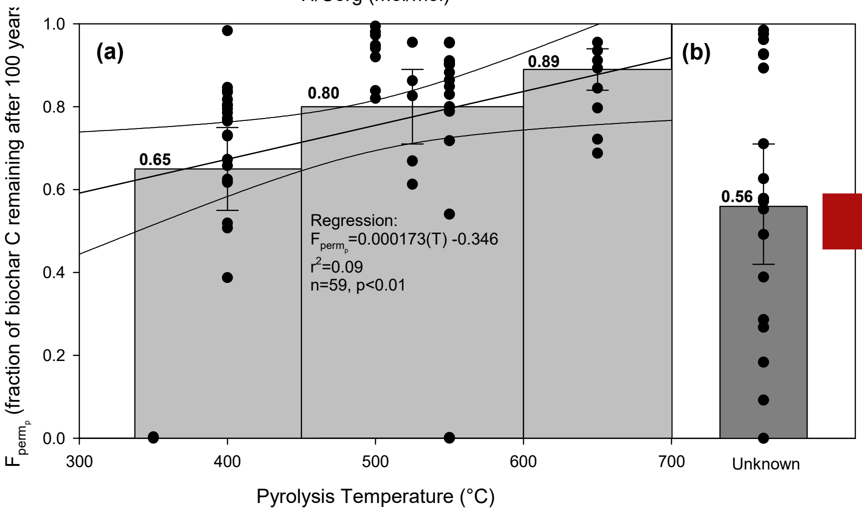
Biochar with higher condensation (=low H/Corg ratios) have greater persistence

(Only experiments longer than one year, 2-pool model, 10°C)

Lehmann et al, 2015, Routledge

Persistence in Soil





Higher pyrolysis temperature ≈ higher condensation

Opportunities for monitoring practice

Challenge for validating persistence over centuries and millennia

New IPCC guidelines for GHG accounting

(Only experiments longer than one year, 2-pool model, 10°C)

Cornell University

Major et al. 2010; Zimmerman 2010; Singh et al. 2012; Zimmerman & Gao 2013; Fang et al. 2014; Herath et al. 2015; Kuzyakov et al. 2014; Dharmakeerthi et al. 2015

Cheng et al 2008; Hammes et al 2008; Lehmann et al 2008; Liang et al 2008; Lutfalla et al 2017; Nguyen et al 2008; ; Preston and Schmidt, 2006, calculated after Gavin et al, 2003; Vasilyeva et al 2011

IPCC Methodology - 2019

EQUATION 4A.1

ANNUAL CHANGE IN BIOCHAR CARBON STOCK IN MINERAL SOILS RECEIVING BIOCHAR ADDITIONS

$$\Delta BC_{Mineral} = \sum_{p=1}^{n} \left(BC_{TOT_p} \bullet F_{C_p} \bullet F_{perm_p} \right)$$

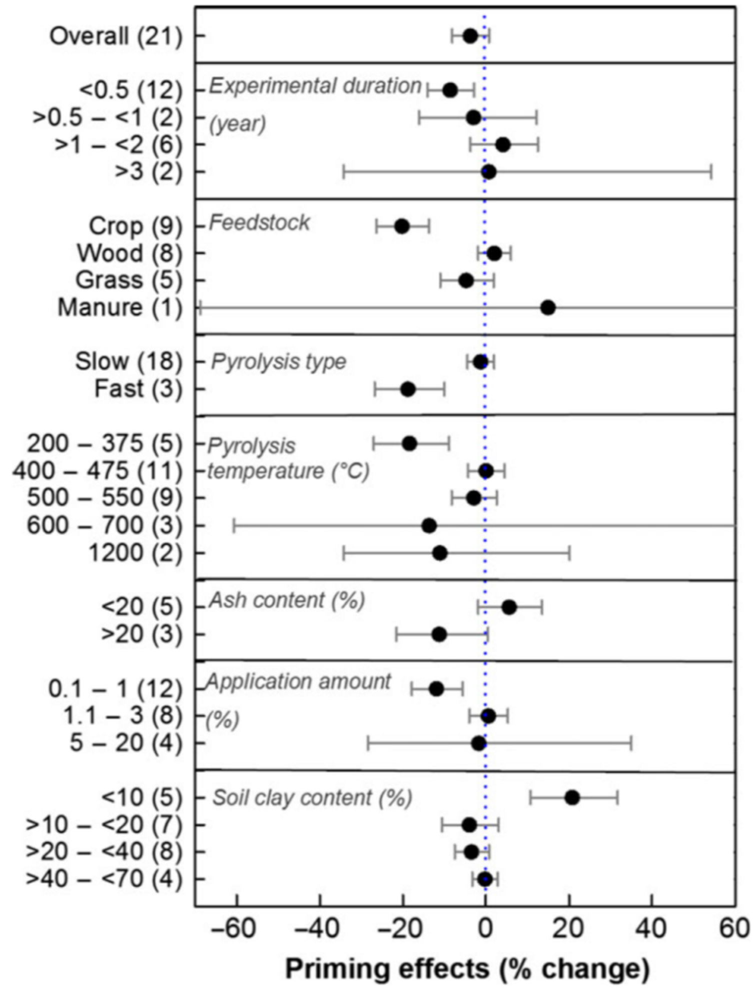
IPCC Methodology - 2019

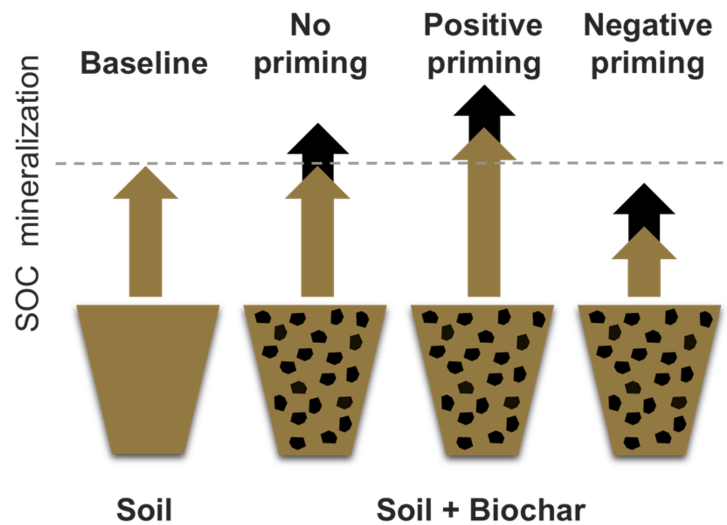
TABLE 4A.1 VALUES FOR ORGANIC C CONTENT FACTOR OF BIOCHAR BY PRODUCTION TYPE (F_{C_p}).		
Feedstock	**Pyrolysis Production Process**	**Values for F_{C_p}** [2]
Animal manure	Pyrolysis [1]	0.38 ± 49%
	Gasification [1]	0.09 ± 53%
Wood	Pyrolysis	0.77 ± 42%
	Gasification	0.52 ± 52%
Herbaceous (grasses, forbs, leaves; excluding rice husks and rice straw)	Pyrolysis	0.65 ± 45%
	Gasification	0.28 ± 50%
Rice husks and rice straw	Pyrolysis	0.49 ± 41%
	Gasification	0.13 ± 50%
Nut shells, pits and stones	Pyrolysis	0.74 ± 39%
	Gasification	0.40 ± 52%
Biosolids (paper sludge, sewage sludge)	Pyrolysis	0.35 ± 40%
	Gasification	0.07 ± 50%

TABLE 4A.2 VALUES FOR F_{perm_p} (FRACTION OF BIOCHAR C REMAINING AFTER 100 YEARS)	
Production	**Value for F_{perm_p}** [1, 2]
High temperature pyrolysis and gasification (> 600 °C)	0.89 ± 13%
Medium temperature pyrolysis (450-600 °C)	0.80 ± 11%
Low (350-450 °C)	0.65 ± 15%

IPCC 2019 Guidelines for GHG accounting

Mineralization of Existing Soil OC by Biochar

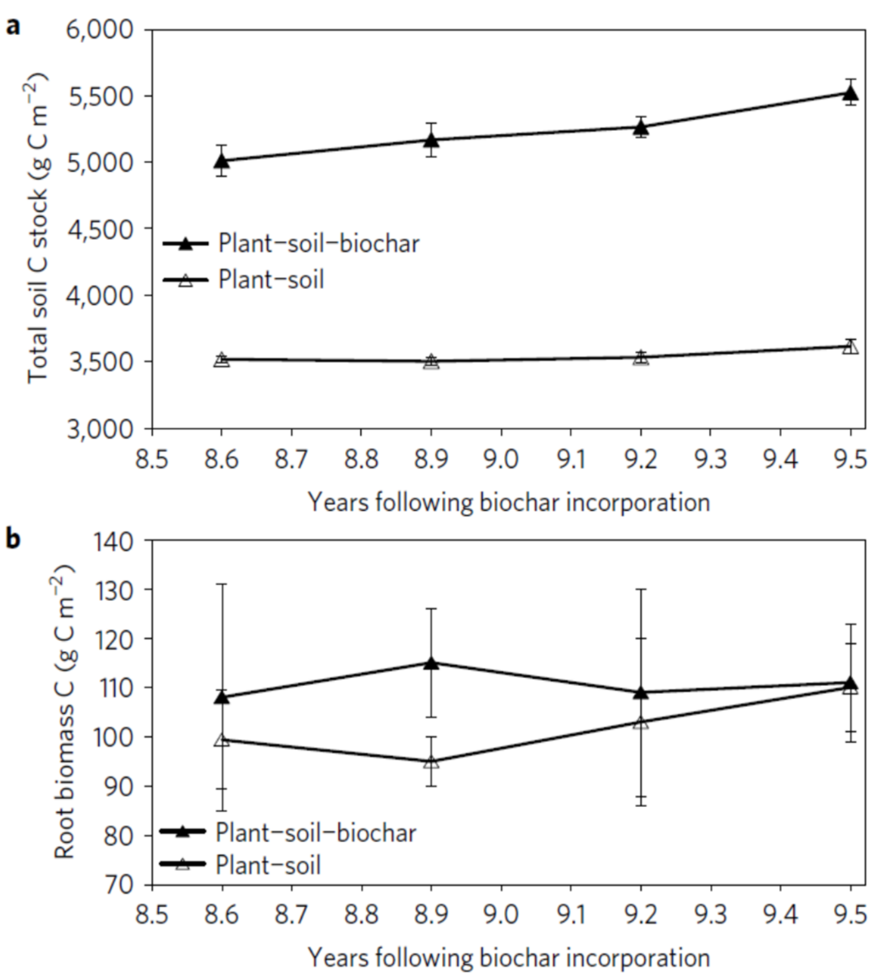


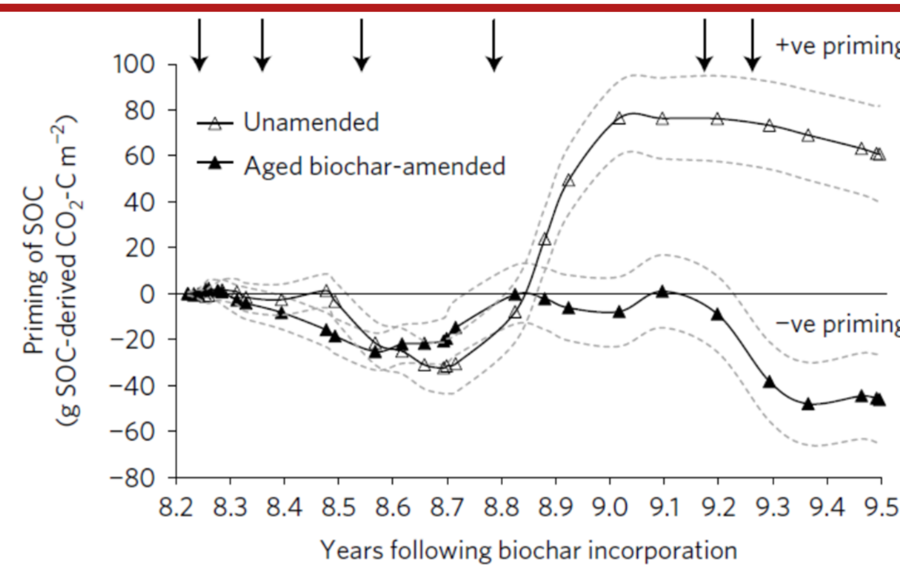


Average mineralization reduction: -3.8% (95% CI = -8.1–0.8%)

Wang et al., 2016 *Global Change Biology* 8, 512-523
Whitman et al, 2015, *Routledge*

Priming of Existing Soil OC by Biochar





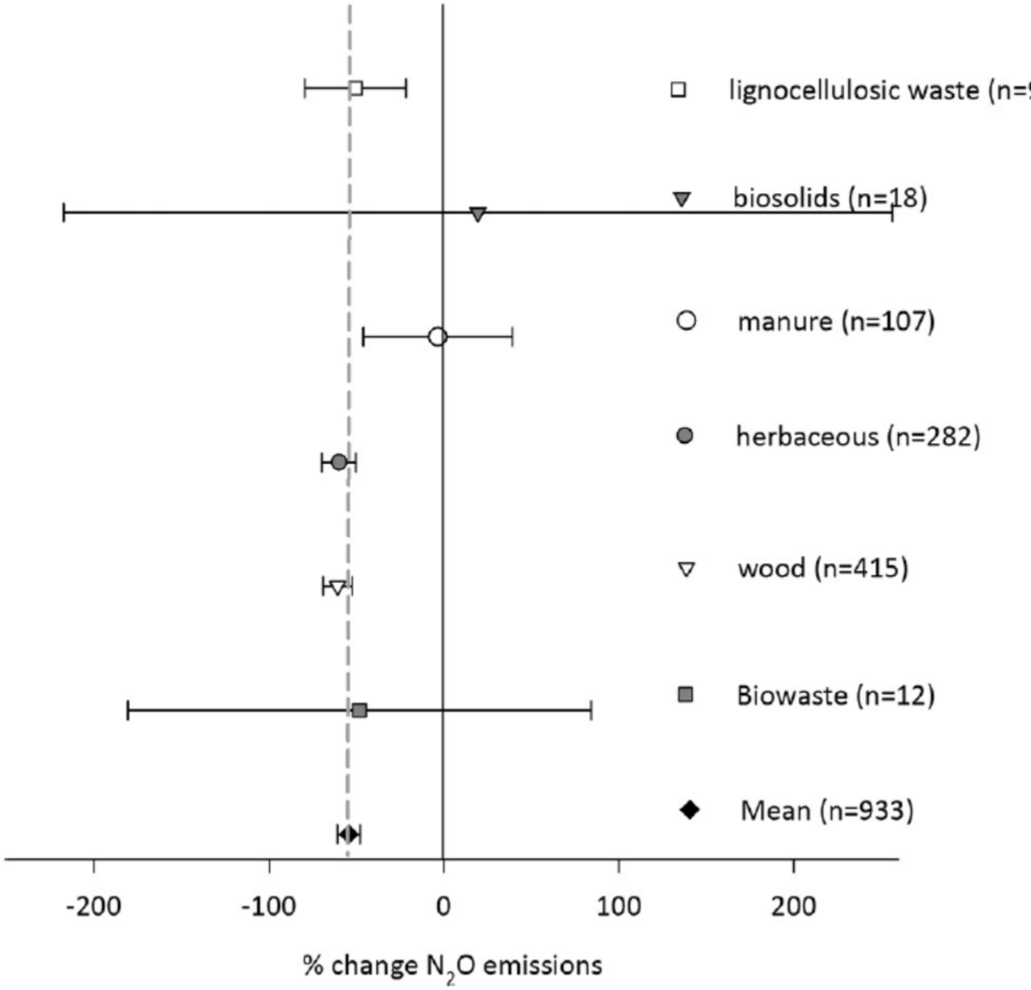
Greater SOC while root biomass unchanged

Negative priming of SOM by 6% and increased recovery of root-derived C by 20%

Nine years after one-time biochar application of 10 t ha^{-1}

Weng et al., 2017 *Nature Climate Change* 7, 371-376

Soil Nitrous Oxide Emissions with Biochar



Average net reduction 54%

(BUT: typically no isotope studies
BUT: wrong control)

(n=30 studies)

Cayuela et al. 2014, *Agr. Ecosys. Env.* 191, 5-16

Biochar as a Soil Amendment

Carbon Product

Carbon persistence

Surface area and functional groups

Electron shuttle and fused arom.

GHG reduction + C sequestration
Soil Health
Pollution reduction by leaching and gas emissions
Soil remediation
Inoculant carriers
Signaling (plant-plant; plant-MO)

Nutrient Product

Nutrient enrichment

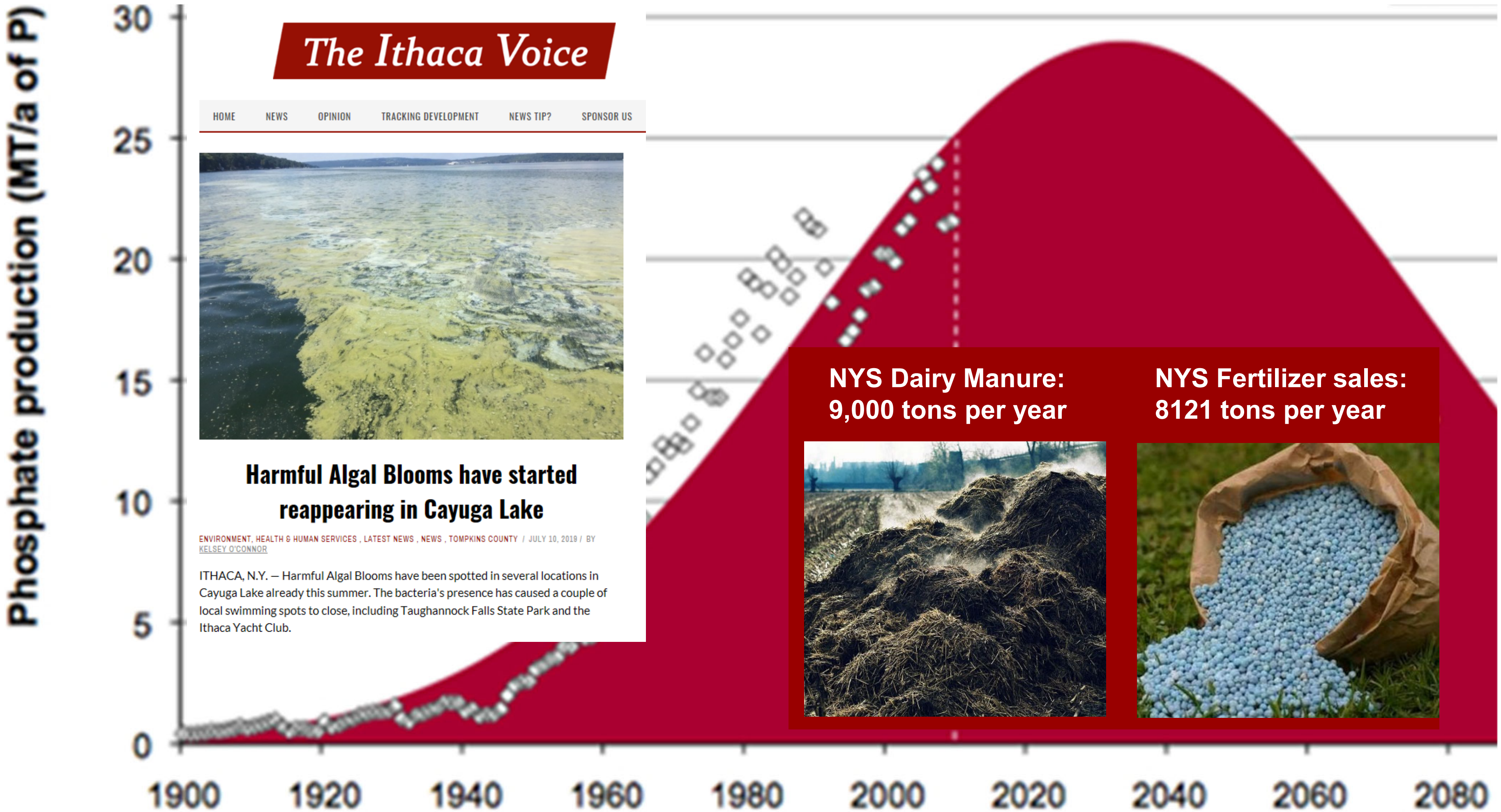
Nutrient availability

Sterilization

Denaturing of pollutants

Fertilization
Pollution avoidance
GHG reduction (+ C sequestration)

Global Supplies and New York Phosphate



Cornell University

Cordell et al. 2011, *Sustainability* 3, 2027-2049
Ketterings and Czymmek K 2012 *What's Cropping Up*

Recycling of Dairy Manure using Pyrolysis

No contaminants (heavy metal, PAH, PCB, dioxin/furans, etc.)
No pollutants from manure (pathogens, hormones, antibiotic)

100 kg liquid dairy manure
0.1% phosphorus

4 kg biochar
2% phosphorus

www.pyrolysis.cals.cornell.edu

INNOVATION CENTER FOR U.S. DAIRY
HEALTHY PEOPLE • HEALTHY PRODUCTS • HEALTHY PLANET

Cornell University

Enders et al., 2019, Soil Sci Soc Am. Ann. Meeting

Recycling of Dairy Manure using Pyrolysis

Value as ingredient of potting mix: appr. $1,900 ton^{-1}
83% from C value
(as potting mix)

Maximum Potential (NYS per year):
$272M value for farmer
$1.3B value for retail

$114M reduced transportation
$4-15M reduced GHG ($20-80/t CO_2e)

Nutrients better available to plants, but less leachable!

Element	Manure		Biochar		Change due to pyrolysis	
	Leachable mg/kg	Available mg/kg	Leachable mg/kg	Available mg/kg	Leachable	Available
Phosphorous	409.8	4505.9	35.8	5088.2	-91%	13%
Potassium	7372.8	8114.2	9399.9	12891.2	27%	59%
Calcium	31257.5	80671.0	33720.8	142276.8	8%	76%
Magnesium	2785.9	6578.6	291.1	7654.5	-90%	16%

Enders et al., 2019, Soil Sci Soc Am. Ann. Meeting

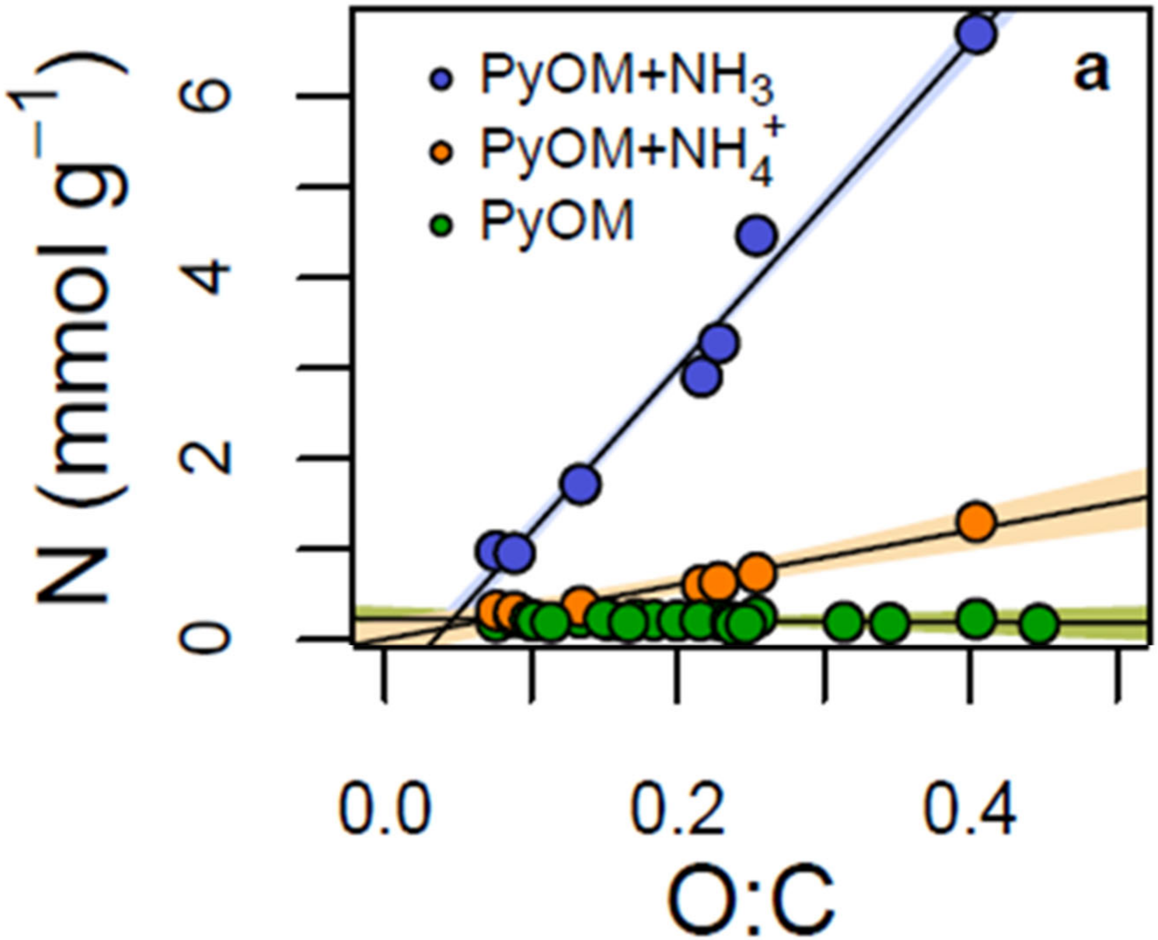
Biochar as Adsorber

Biochar	Solution	Total N before urine (%w/w)	Total N after urine (%w/w)	**ΔN after urine (%w/w)**
500°C HSW	**Fresh urine + HCl**	3.33 ± 0.08	4.47 ± 0.17	**1.14 ± 0.19**
	Fresh urine		3.59 ± 0.05	0.26 ± 0.09
	Deionized water		3.71 ± 0.02	0.38 ± 0.08

- N retention primarily NH_4^+ at pH <7
- Greater than predicted by CEC, 1.14% vs. 0.31% (w/w)

Krounbi, prelim. data

Biochar Oxidation and NH_3 Retention

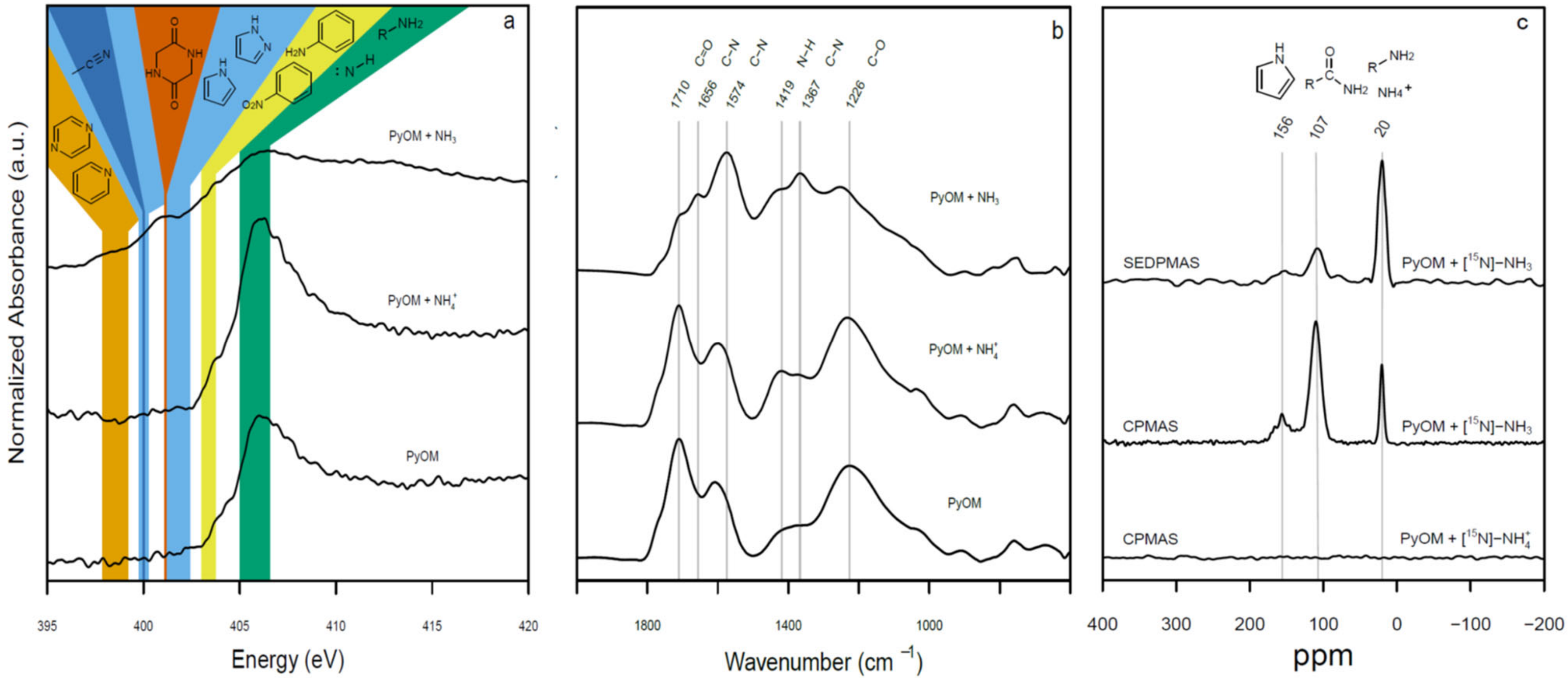


Up to 18% N

Biochar Oxidation and NH_3 Retention

>50% N retained through chemisorption rather than physisorption

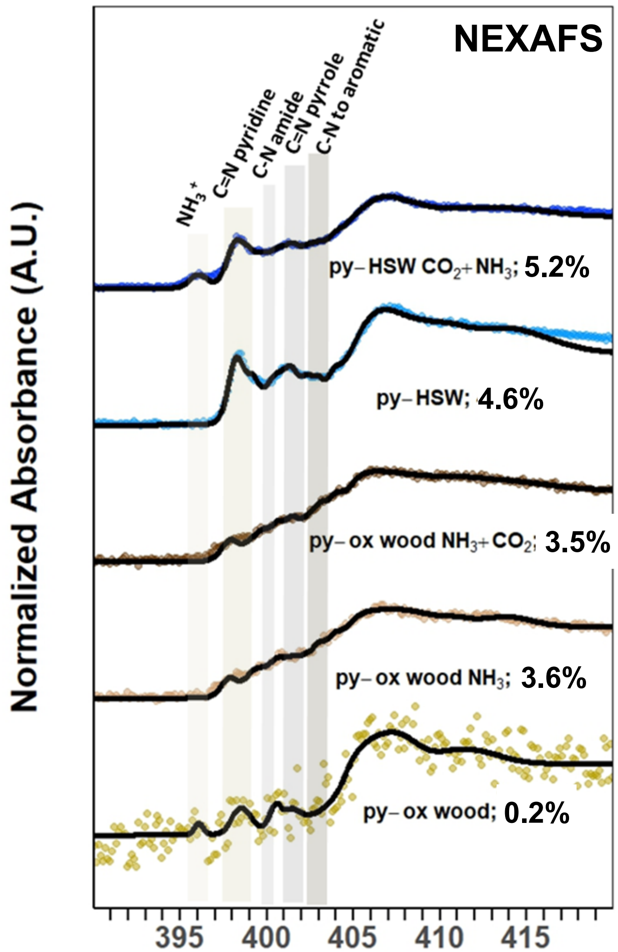
>10% in heterocyclic structure

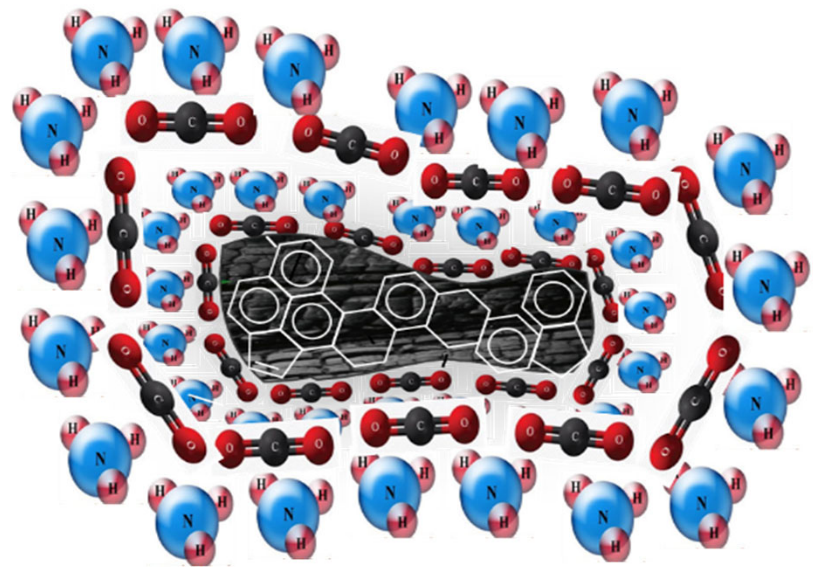


Cornell University

Hestrin et al, 2019, *Nature Communications* 10, 664

Biochar as Nitrogen Adsorber

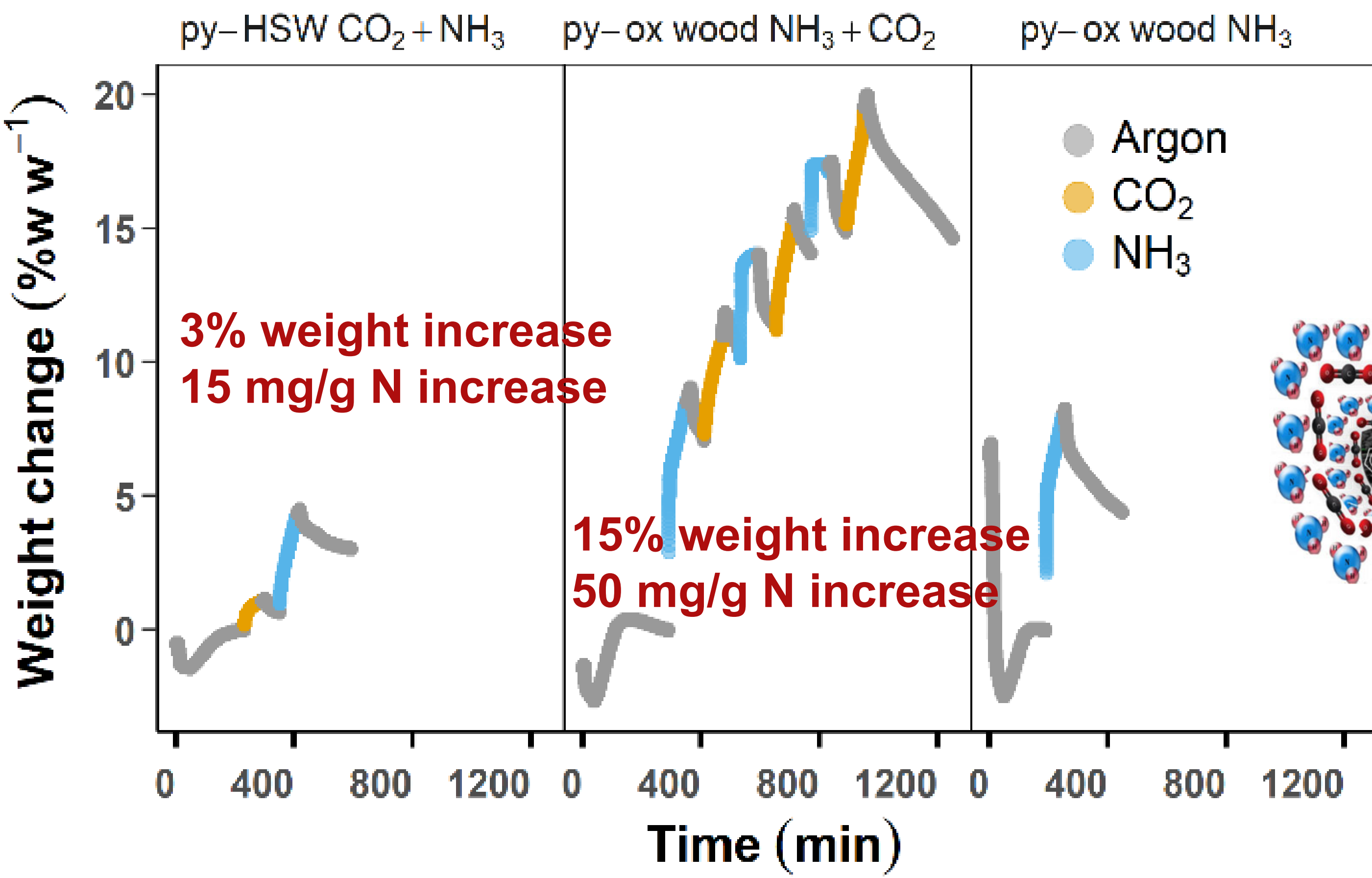


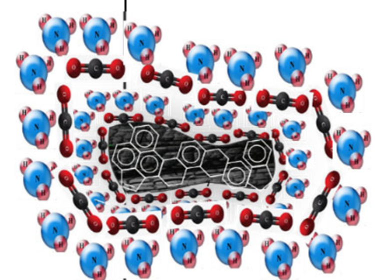


Biochar from N-rich human solid waste
(solid-liquid separating toilets, Nairobi)

Krounbi et al., submitted

Biochar as Nitrogen Adsorber

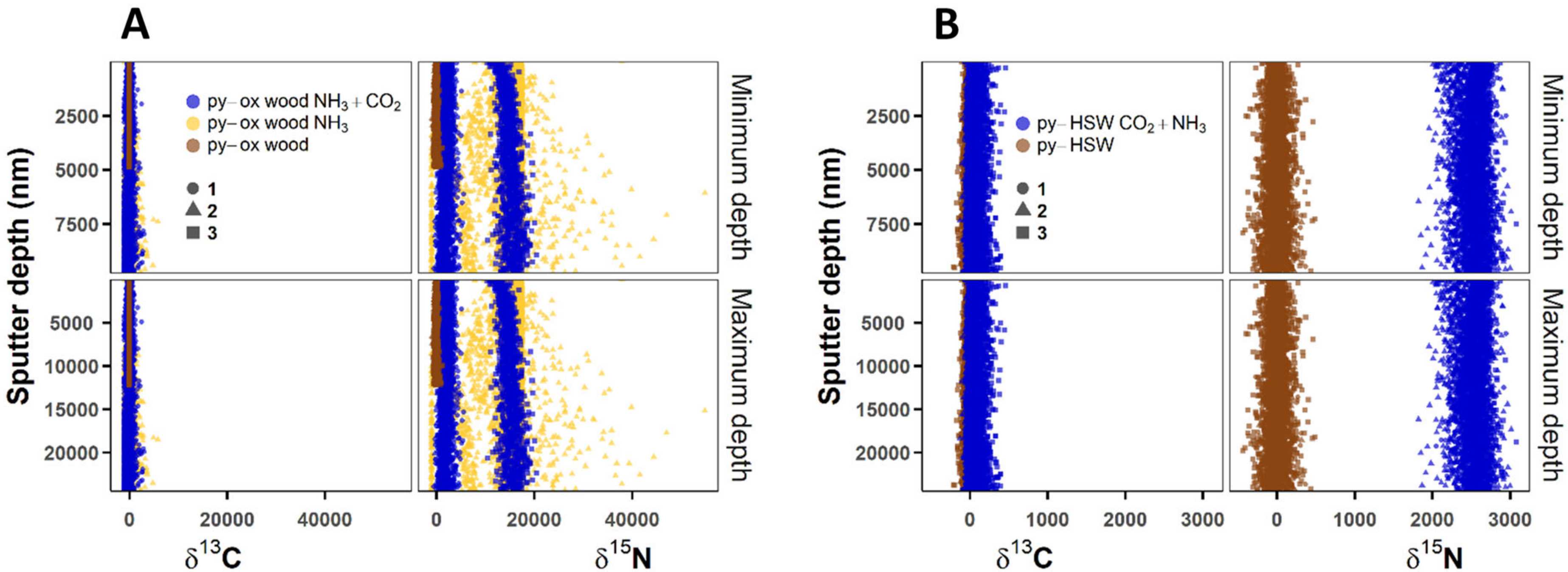




Krounbi et al., submitted

Biochar as Nitrogen Adsorber

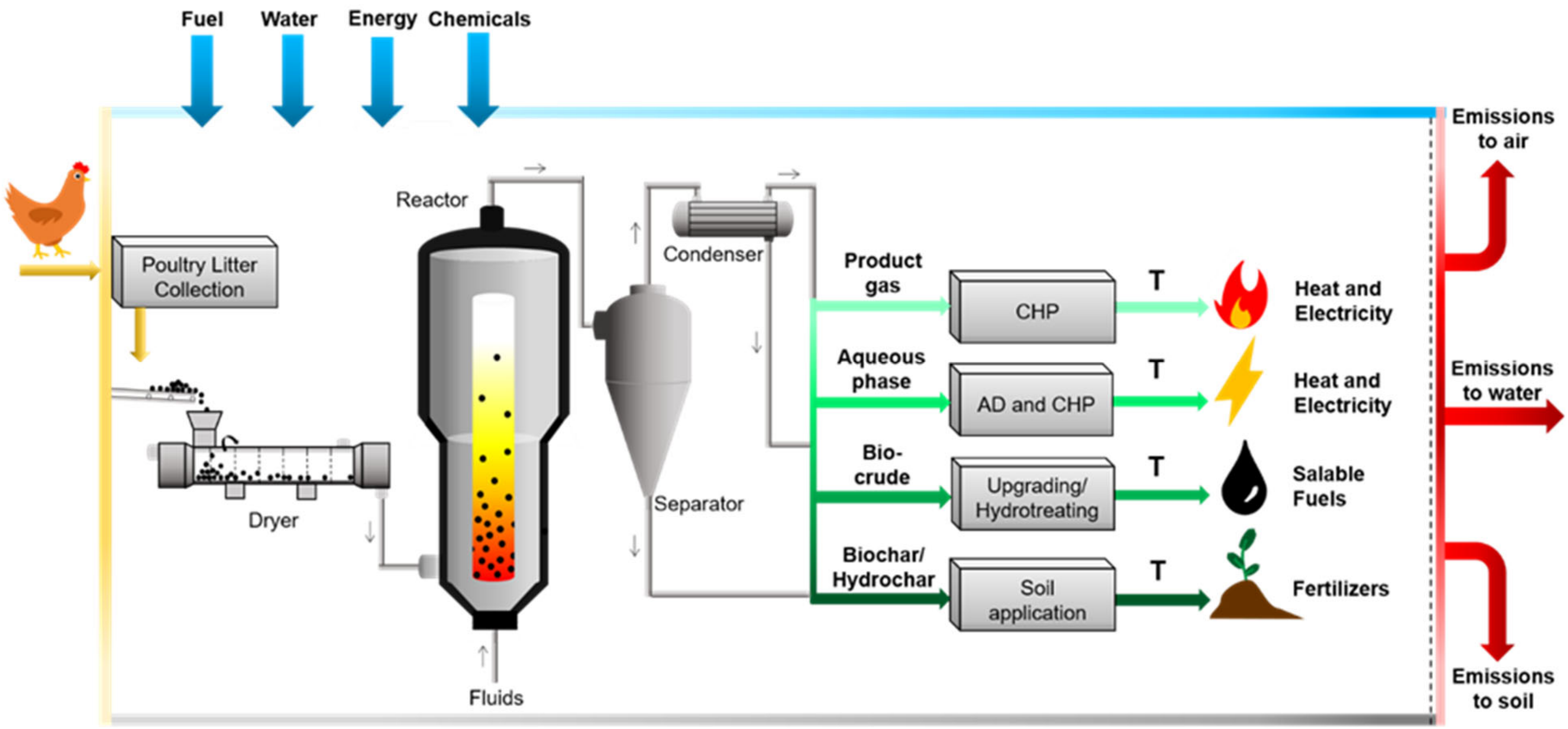
>7 μm depth of NH_3 into biochar material



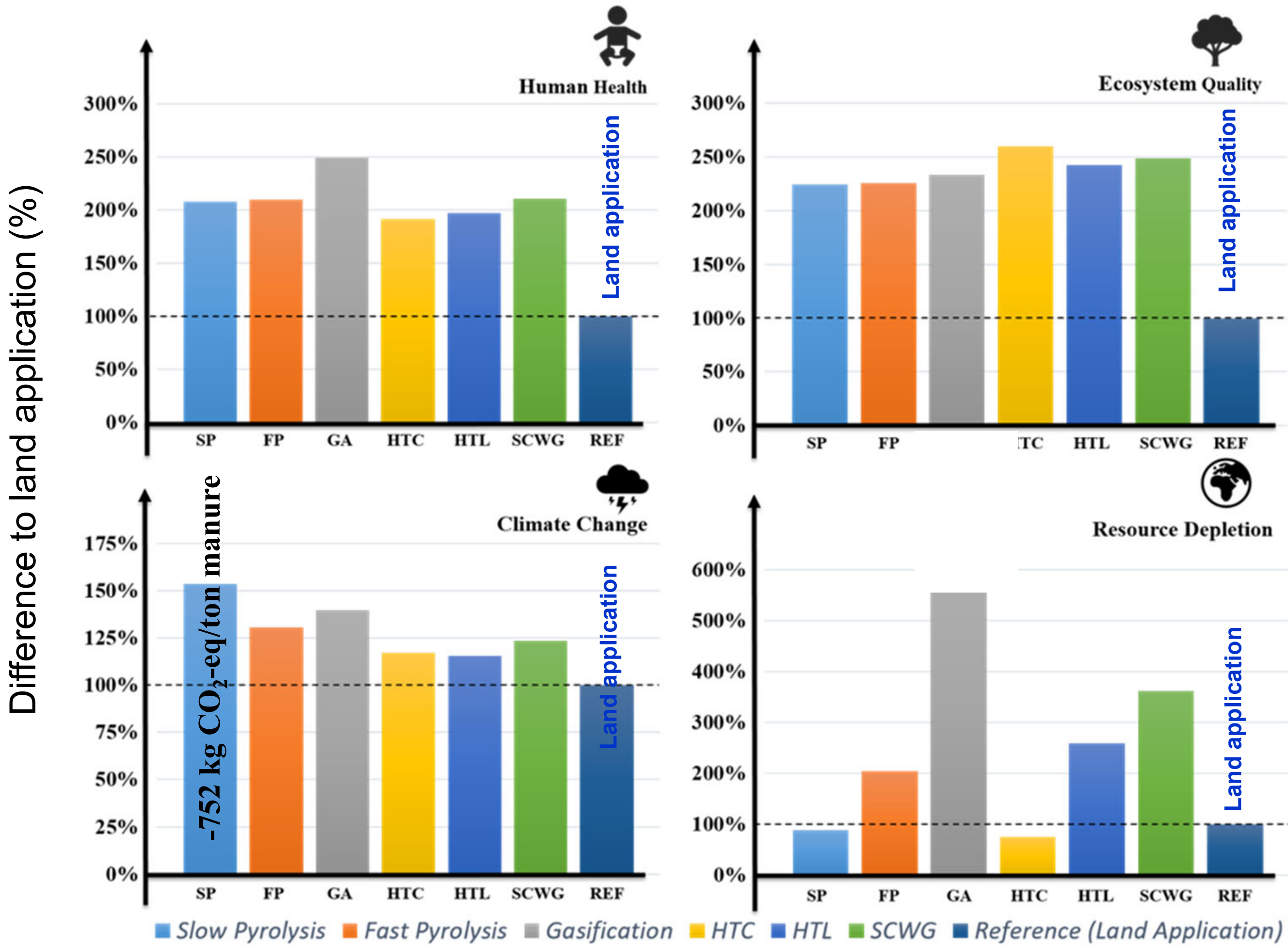
NanoSIMS

Krounbi et al., submitted

Poultry Litter Processing



Environmental Benefits



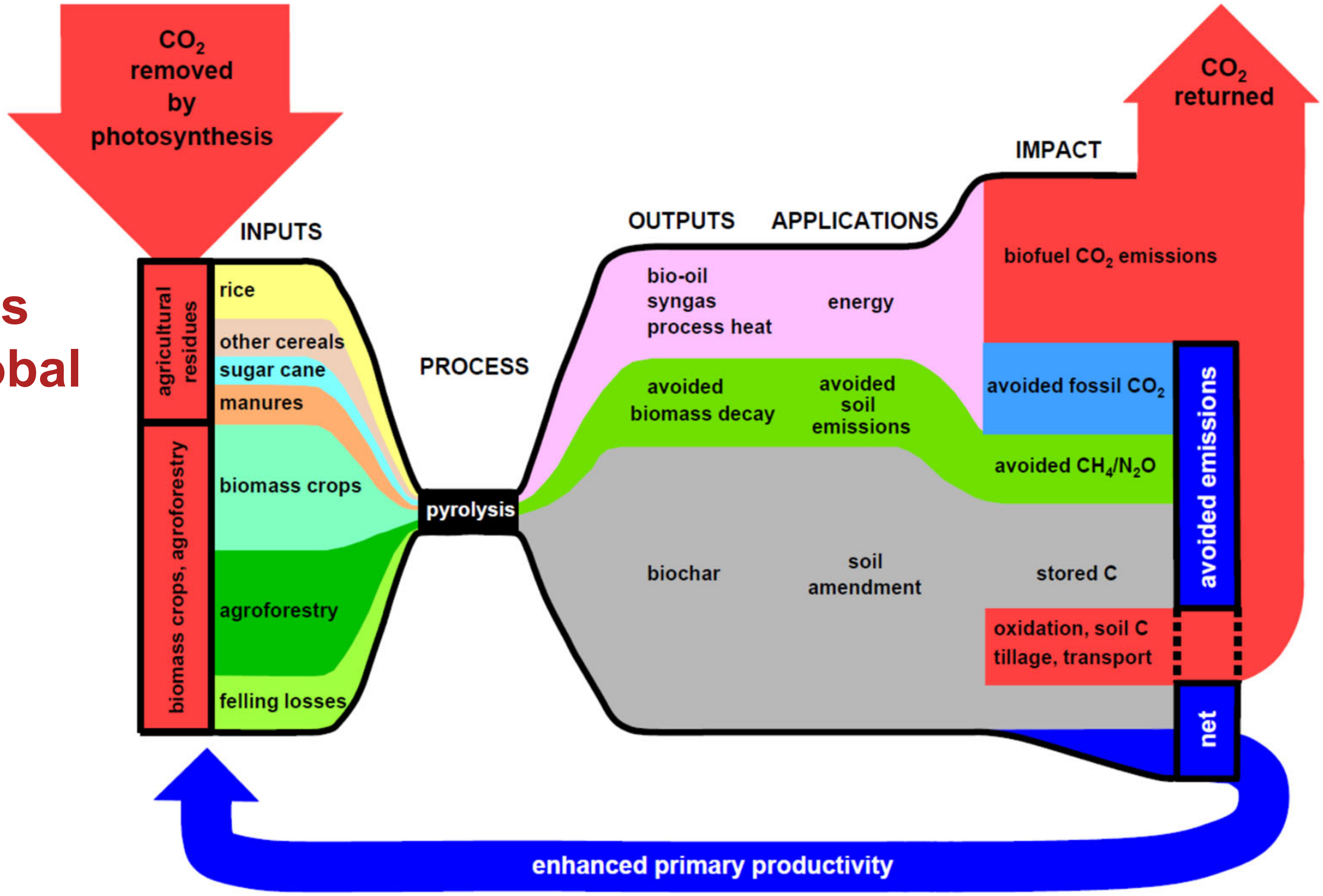
Lei, Bora et al., 2019, in preparation

SCWG supercritical water gasification

Cornell University

Climate Change Mitigation – Life Cycle

Manure wastes missing in global assessments



Woolf et al, 2010, *Nature Communications 1, 56*

Take-Home Messages

- Biochar system with nutrient-rich feedstocks delivers resource as well as GHG benefits

  BUT: technology development needed

- Lower life-cycle emission reductions of biochar systems than SOC accrual alone

  BUT: Lots of moving parts that need monitoring (N_2O, time horizon…), not only with biochar systems…

- Trade-offs between food production and C accrual is different between external and internal C source approaches and environmental/water burden not considered

  BUT: Yield/water prioritization of land managers/costs